FORMATION OF EUCRITES AND DIOGENITES ON A VESTA-SIZED ASTEROID: I. CORE FORMATION.

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INTRODUCTION

Core formation in asteroid-sized planetesimals occurred early (< 15 Ma after T_0) as has been recently demonstrated [1,2] using $^{182}W/^{184}W$ ratios. Depletion of siderophile elements in the mantle of the HED parent body has been cited as evidence that metal had segregated into a core before the eucrites formed (see e.g., [3]). Calculations [4] and experiments [5] indicate that large degrees of melting are required to efficiently separate metal from silicate. Given the siderophile element data, it seems necessary to have large amounts of melting on a Vesta-sized body in order to facilitate core formation. The high temperatures necessary to melt a chondritic mantle could be provided early (2-5 Ma after T_0) by the decay of ^{26}Al to ^{26}Mg ($T_{1/2}$ = 0.7 Ma; [6]) and ^{60}Fe to ^{60}Ni ($T_{1/2}$ = 0.3 Ma; [7]), by a hot T Tauri or FU Orionis stage, or a superluminous sun. We [8] examined the issue of core formation in a CI chondritic HED parent body by considering siderophile element partitioning during metal-silicate equilibrium at high temperatures. Here we extend this work to investigate the effect of bulk composition by considering CM, CO, CV, H, L, and LL chondritic starting materials.

MODELING CORE FORMATION IN ASTEROIDS

Moderately siderophile elements in the HED parent body mantle

Nickel and Co concentrations in the HED parent body mantle are estimated using correlations with bulk MgO+FeO (e.g., [9]). The slope of terrestrial basalt and mantle peridotite samples in each case is approximated and applied to the HED suite to estimate the HED mantle Ni and Co contents. Molybdenum, W and P concentrations are estimated by correlations with a reference refractory lithophile element — we use both La and Ce. Since the ratios of W/Ce, Mo/Ce and P/La are the same in terrestrial basalts, komatiites, and mantle peridotites, the eucrite basalts can be used to estimate these ratios in the HED parent body mantle. Knowing the basaltic ratios and the abundance of the reference refractory lithophile incompatible element for a broad range of ordinary and carbonaceous chondrites [10], the mantle abundance of an incompatible siderophile element following core formation can be calculated (Table 1).

Mass balance constraints

The distribution of a siderophile element (*i*) in a planetary body that has undergone core formation can be understood in terms of the following mass balance equation:

$$C^i_{bulk} = x[C^i_{LS}[p + (1-p)D^i_{SS/LS}]] + (1-x)[C^i_{LS}[mD^i_{LM/LS} + (1-m)D^i_{SM/LS}]] \quad (1)$$

where x = silicate fraction of the planet; p = fraction of the silicate that is molten; and m = fraction of the metal that is molten; C^i_{LS} and C^i_{bulk} are concentrations of siderophile elements in the liquid silicate and bulk portions of the planet; $D^i_{LM/LS}$ is the liquid metal / liquid silicate partition coefficient, and $D^i_{SM/LS}$ is the solid metal / liquid silicate partition coefficient, and $D^i_{SS/LS}$ is the solid silicate / liquid silicate partition coefficient (see [11] for full derivation of mass balance equations and method to calculate metal/silicate partition coefficients as a function of P, T, fO_2 and composition).

RESULTS OF MODELING

There are many variables involved in modeling core formation, even in a small body. Several of these variables are interdependent, and thus can be linked in the modeling. For instance, the fractions of molten silicate and metal (p and m, respectively) will be related to temperature. In a study of the melting behavior of the terrestrial upper mantle [12], p was estimated based on temperature variations and knowledge of the liquidus and solidus temperatures. We have used this approach for estimating both p and m as a function of temperature in our calculations; chondrite liquidus and solidus temperatures were taken from [5] and [13] and where necessary those for metal were taken from the Fe-S phase diagram (e.g., [14]). Similarly, the sulfur content of the metallic liquid (X_S) can be estimated as a function of temperature by fitting a polynomial to the liquidus surface of the Fe-S diagram. Using the mass balance equations (1), and fixing as many variables as possible, C^i_{mantle} can be calculated for the five moderately siderophile elements at specific conditions to determine if the mantle abundances in Table 1 can be matched.

For a magma ocean scenario on a Vesta-sized body, pressure is not more than 2 kb, a magma ocean would be peridotitic (highly depolymerized silicate melt), and the oxygen fugacity is known to be lower than the iron-wüstite oxygen buffer (IW); these variables can be fixed in the calculations. The remaining variables are bulk composition (C^i_{bulk}), core size (1-x), and temperature (T), with the latter linked to p, m and X_S as described above. Even with a range of ordinary and carbonaceous chondrite starting materials, the conditions for metal-silicate equilibrium (as deduced from the siderophile element abundances) are similar in each case. The core sizes range from 6 to 22 %, sulfur contents from X_S = 0.05 to 0.21. The temperatures range from 1500 to 1530 ˚C, mostly molten mantle (p = 0.64 to 0.78), and mostly molten metal (m = 0.94 to 1.00). The Ni contents of the segregated cores range from 7 to 40%. In a companion abstract we model the crystallization history of molten mantles of composition resulting from subtraction of the metallic cores from bulk chondrite compositions (supported by NASA Grant NAGW-3348 to MJD)

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Table 1: Summary of core formation models

	H	L	LL	CI	CM	CO	CV
estimated mantle							
Ni (ppm)	75	55	40	80	76	73	70
Co (ppm)	25	24	23	26	25	23	24
Mo (ppb)	3.7	4.1	4.1	2.7	3.8	4.6	5.8
W (ppb)	13	14	14	9	12	15	19
P (ppm)	49	51	52	39	52	64	80
modeled mantle (Eqn. 1)							
Ni (ppm)	136	92	84	103	96	119	161
Co (ppm)	24	17	17	16	17	22	32
Mo (ppb)	2.0	1.7	2.8	1.7	3.0	2.4	2.1
W (ppb)	21	15	19	9	14	14	18
P (ppm)	72	62	126	37	27	57	81
conditions for best fit							
T (˚C)	1530	1527	1527	1517	1502	1527	1527
Δ IW	-2.4	-2.2	-1.8	-2.3	-2.0	-2.4	-2.5
core mass (%)	14	17	20	15	22	12	6
‡ frac. of mantle molten (p)	0.78	0.77	0.77	0.68	0.64	0.71	0.71
‡ fraction of core molten (m)	0.99	0.98	0.98	0.96	0.94	0.98	0.98
†X_S	0.05	0.10	0.17	0.10	0.15	0.15	0.21

columns represent the results of our modeling for specific chondrite compositions (tabulated by [10]).
'estimated mantle' values are calculated using chondrite siderophile element abundances and analyses of eucrites and diogenites, whereas 'modeled mantle' values are calculated the mass balance constraints of Eqn 1.

‡ the fraction of molten material was estimated using the approach of [12]; if both liquidus and solidus temperatures (T_l and T_s, respectively) are known, then the fraction of molten material (p or m) can be estimated as a function of temperature by p (or m) = $T' + (T'^2 - 0.25)(a_0 + a_1 T') + 0.5$, where a_0 = 0.4256 and a_1 = 2.988, and T = (T-(Tl-Ts)/2) / (Tl-Ts). Values for T_l and T_s, are from [5] and [13] for chondrites, and [14] for the Fe-S system.

† in cases where the temperature was below the liquidus surface of the Fe-S system, the liquid S content was constrained to be that required by the Fe-S phase diagram reported by [14]. A polynomial fit to the liquidus surface is: $X_S = -2.1146 + (0.0041135)T - (1.6424\times10^{-6})T^2$, where T is in kelvins.